AD-E001412

(12)

ARVIN/CALSPAN

IR AND VISIBLE WAVELENGTH OBSCURATION BY PYROTECHNICALLY GENERATED ALKALI-HALIDE SMOKES

BY

J.T. Hanley, J.N. Kile, B.J. Wattle and E.J. Mack

January 1983

Calspan Report No. 7031-M-1
Contract No. N00014-82-C-2108

MAY 4 1983

Prepared for:
NAVAL RESEARCH LABORATORY
4555 OVERLOOK AVENUE, S.W.
WASHINGTON, D.C. 20375
CODE: 4320

ADVANCED TECHNOLOGY CENTER

PO BOX 400 BUFFALO NEW YORK 14225 TEL (716) 632-7500

83 03 14 107

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Section 1

INTRODUCTION AND SUMMARY OF RESULTS

Background

Under Contract No. N00014-82-C-2106 with the Naval Research Laboratory, Calspan Corporation continued its laboratory evaluation of hygroscopic pyrotechnic smoke screens, a collaborative investigation with several Navy laboratories now in its fifth year.* The overall objective of the program is the development of an effective screening agent to both visible and IR wavelengths utilizing pyrotechnically-generated hygroscopic aerosol. Calspan's primary role in the Navy program is to evaluate the extinction performance of pyrotechnics developed by the Naval Weapons Center and to provide recommendations directed at improving the extinction performance of these smokes. The evaluation is conducted in Calspan's 600 m^3 test chamber and includes measurement of the smokes' mass extinction coefficient, yield factors, chemical composition and particle size distribution.

In general, the NWC pyrotechnics are formulated to produce smokes of alkali-halide salt particles upon combustion. The primary advantage of such pyrotechnics is their ability to produce copious numbers of hygroscopic aerosol, which, when exposed to a sufficient level of ambient humidity, deliquesce to form solution droplets of approximately twice their original size and five times their original mass. Thus, only a fraction of the resultant cloud mass (smoke screen) originates from the pyrotechnic, the remaining mass being supplied by atmospheric water vapor.

Objectives of Current Program

In pursuit of an effective IR wavelength screen and an increased understanding of the particle formation mechanisms and resultant size distribution, this year's efforts focused on two primary objectives:

---

* The first four years of the investigation were conducted under the sponsorship of the Naval Air Systems Command, AIR 32R (formerly AIR 310C).

1. Through a series of chamber tests, assess the visible and IR wavelength extinction characteristics of four recently developed NWC pyrotechnics: LiCl#1, LM9, LM11 and LM12.

2. Through a series of chamber tests conducted by Calspan with participants from NRL and NWC, investigate the smoke particle size distribution as functions of pyrotechnic and associated burn parameters.

Summary of Major Results

Results from this year's tests show that the new NWC smokes significantly outperform all previous NWC smokes tested by Calspan on this program. At IR wavelengths the newly developed LM12 pyrotechnic provides up to 40 times the extinction of CY85A. Its superior IR performance is attributed to the combined effects of absorption by the ~25% (by weight) carbon content of the LM12 smoke and scattering by relatively large smoke aerosol.

Improvements were also measured for visible wavelength extinction. The LM9 pyrotechnic, generating a very hygroscopic LiCl aerosol, provided from 2 to 4 times the extinction of CY85A chiefly through scattering effects.

A limited study of factors affecting the size distribution of the pyrotechnic smokes revealed that aerosol size is dependent upon both payload mass and pyrotechnic ventilation. Increased payload mass led to increased particle size believed due to an increase in the concentration of condensable gases generated by the pyrotechnic as well as aerosol coagulation within the chamber. Ventilation of the pyrotechnic during combustion diluted the condensable gases resulting in decreased particle size.

The above topics are discussed in greater detail within the body of this report. Section 2 describes the chamber facility, instrumentation and test procedures. Results of the extinction and mass yield measurements are presented in Section 3. Section 4 presents the results of the size distribution measurements. The major conclusions drawn from this year's efforts and recommendations for future work are presented in Section 5.

Definition of extinction and yield parameters is provided in Appendix A. Appendix B presents a limited comparison of the NWC smokes to white phosphorus.

Section 2

FACILITIES AND PROCEDURES

2.1 Facilities and Instrumentation

The Calspan chamber is cylindrical with a diameter and height of 9.1 meters enclosing a volume of 590 m^3. The inner chamber surface is coated with a fluoroepoxy type urethane (developed at the Naval Research Laboratory, Washington, DC) which has surface energy and reactivity properties comparable to those of the FEP Teflon. A complete air handling capability permits the removal of virtually all particulate and gaseous contaminants prior to each experiment, the introduction of specified aerosols, and control of humidity from 30 to 97% RH.

Instrumentation used to monitor aerosol behavior within the chamber included visible and IR wavelength transmissometers, a Thermo Systems Model 3030 Electrical Aerosol Analyzer (EAA), and MRI Integrating Nephelometer, a Gardner Associates Small Particle Detector, and a Royco Optical Particle Counter. Specific details of the instrumentation and chamber facility may be found in prior reports (References 1-4).

Extinction of electromagnetic radiation by the pyrotechnic smokes was measured at visible wavelength over a path of 2.7 m. A lense collimated beam from an incandescent bulb powered by a regulated power supply was focused on an RCA 4440 photomultiplier detector. The photomultiplier has a peak sensitivity in the range 0.4-0.5 um wavelength.

The IR transmissometer utilizes an 18.3 m path length, a 900°C black body source, and an HgCdTe detector operated at liquid nitrogen temperature. The source beam, chopped and collimated, is directed through the chamber (at a height of 1.5 m) and folded back to the detector by spherical front silvered mirrors. Continuous measurements of extinction as a function of wavelength are obtained via a variable wavelength filter wheel located in front of the detector. The spectral resolution of this filter is two percent over the wavelength interval from 2.5-14 um. Data acquisition and reduction is computer controlled. Intensity measurements are obtained at approximately 0.02 um wavelength intervals, with a complete 2.5-14 um scan requiring 2 minutes.

2.2 Generation of Pyrotechnic Smokes

Prior to each test, the chamber was filtered of background aerosol and brought to the desired relative humidity. A preweighed quantity of the pyrotechnic was then ignited within the chamber using a propane torch. After allowing several minutes for the smoke to become uniformly mixed and for the hygroscopic aerosol to come to equilibrium at the chamber humidity, measurements were made of appropriate parameters. The smokes were continuously stirred to insure homogeneous conditions throughout the chamber during each test.

2.3 Mass Loading Samples

Mass loading aerosol samples were drawn upon Pallflex type QAOT quartz fiber filters. Sampling duration was typically fifteen minutes at a nominal rate of 1 cfm. Sample flow rate was controlled by use of a calibrated 1 cfm critical orifice with appropriate flow correction for upstream vacuum. To assure the attainment and maintanance of critical flow through the orifice, both upstream and downstream vacuums were monitored. Additionally, a flowmeter was placed in the sampling line providing a direct visual check of the flow rate.

Assessment of aerosol mass loading within the chamber involved the acquisition of three filter samples (one background and two smoke samples) as follows: after bringing the chamber to the desired test humidity, a background filter sample was drawn to assess the mass change due to the inherent hygroscopicity of the filter material. Upon completion of the background sample, the pyrotechnic was ignited. After waiting five minutes for the aerosol to become uniformly mixed throughout the chamber, the two mass loading samples, drawn in sequence, were obtained. The second mass loading sample was obtained primarily as a check on the first, though it also provided an indication of the smoke mass decay rate due to aerosol fallout.

Due to the hygroscopicity of the smoke samples, the filters were weighed directly within the chamber environment immediately after sampling. In this way, errors caused by condensation upon or evaporation from the hygroscopic samples due to exposure to humidities different from those of the test humidity were avoided.

To assess the nominal aerosol mass loading, the filter samples were removed from the chamber, baked at 110°C for one hour to remove all condensed water, and reweighed.

Section 3

EXTINCTION AND MASS YIELD MEASUREMENTS

3.1 Log of Experiments

Table 1 presents a complete log of the chamber tests performed on the current program. For each test, the pyrotechnic payload and chamber relative humidity are presented along with the type of data obtained. These data include visible and IR wavelength extinction measurements, yield factors obtained from mass loading samples, aerosol size distributions and chemical composition analyses of the aerosol smokes.

In all, 23 tests were performed. In tests 1-5 and 7-14, a relatively small payload was ignited for assessment of aerosol size distribution at low concentration followed by ignition of a larger payload for assessment of size distribution at higher aerosol concentrations and/or extinction measurements.

Tests 1-14 were conducted jointly with NRL, NWC and Calspan personnel in March 1982. Tests 1-6 were primarily concerned with evaluating the extinction characteristics of a recently developed NWC pyrotechnic, LiCl#1, relative to the performance of CY85A. Tests 7-14 were then devoted to measurement of the aerosol size distribution for a number of NWC smokes as indicated in the table.

Tests 15-23 were conducted solely by Calspan during late October 1982. These tests centered on extinction and mass yield measurements of three newly developed NWC smokes: LM9, LM11 and LM12.

The primary constituent of the smokes generated by the LiCl#1 and LM9 pyrotechnics is lithium chloride. LM11 and LM12 generate a mixed smoke containing magnesium chloride and carbon. Due to the carbon, the LM11 and LM12 smokes are black, unlike the white smokes of LiCl#1, LM9 and CY85A. Further information on the chemical composition of the smokes is provided in the next section followed by an evaluation of their extinction performance.

Table 1

Log of Chamber Tests Conducted During FY82

TEST PARAMETERS				DATA OBTAINED				
Exp. No.	Pyrotechnic	Payload (g)	RH (%)	Extinction VIS	Extinction IR	Mass Yield	Size Spectra	Chemical Analysis
1	CY85A	0.5 & 160	16	X	X	X	X	
2	CY85A	0.5 & 160	34	X	X	X	X	
3	LiCl#1	0.5 & 80	33	X	X	X	X	
4	LiCl#1	0.5 & 80	69	X	X	X	X	
5	LiCl#1	0.3 & 80	84	X	X	X	X	
6	CY85A	80	89	X	X	X		
7	CY85A	0.5 & 5	40				X	
8	LiCl#1	0.5 & 5	37				X	
9	NYC164	0.5 & 5	36				X	
10	LiCl#1	0.5 & 5	35				X	
11	NWC79	0.5 & 5	30				X	
12	NWC78	0.5 & 5	37				X	
13	CY85A Ventilated	0.5 & 5	39				X	
14	CY85A Chimney	0.5 & 5	40				X	
15	CY85A	160	31	X	X	X		X
16	LM9	80	42	X	X	X		X
17	LM11	80	40	X	X	X		X
18	LM12	80	39	X	X	X		X
19	CY85A	80	86	X	X	X		
20	LM9	80	83	X	X	X		
21	LM11	80	86			X		
22	LM12	80	87	X	X	X		
23	LM11	80	88	X	X	X		

3.2 Chemical Composition of the Pyrotechnic Smokes

Low volume filter samples obtained for mass-loading measurements during the low humidity tests were analyzed for elemental composition of the aerosolized pyrotechnic. Analysis for K, Mg, Na, Ca, and Li was performed by atomic absorption spectroscopy. Ion chromatography was used to determine Cl content. Methodology for estimation of carbon content is described below.

Carbon was determined by heating the samples to 600°C to volitalize the carbon off the samples (through the conversion of carbon to gaseous CO_2) followed by reweighing. Three samples each for LM11 and LM12 were analyzed in this manner. Carbon content for LM11 averaged 36% (27.8, 37.4, 43.8%) and for LM12, 20% (17.4, 19.3, 22.4%). Due to the range of carbon content values for each smoke, these data are considered as only estimates of the actual carbon content.

Attempts were made to determine sample insoluble content by water leaching the previously weighed filter samples followed by baking and reweighing of the residual insoluble matter. Unfortunately, filter wash-out during the leaching process percluded accurate gravimetric determination of the sample insoluble content.

These results, together with the chemical composition of the bulk pyrotechnic (as provided by Dr. L. Mathews, NWC, China Lake), are presented in Table 2.

As can be seen in Table 2, LiCl#1 and LM9 are similar pyrotechnics, the only difference being binder content. It was observed during the March 1982 test series that LiCl#1 had an excessive binder content resulting in a reduction of the overall pyrotechnic performance. The pyrotechnic was then reformulated (to LM9) by NWC to have a lower binder content and was available for the second (October) test series.* As only the binder content of the pyrotechnic was changed, both LiCl#1 and LM9 are expected to generate similar smokes.

---

* We gratefully acknowledge the assistance of Dr. L. Mathews (NWC, China Lake) and his associates for the timely preparation and delivery of the LM9 and other pyrotechnics.

Table 2

Composition by Weight Percent of the NWC Alkali-Halide Pyrotechnics and Resultant Smokes

BULK PYROTECHNIC COMPOSITION (NWC)

	CY85A	LiCl#1	LM9	LM11	LM12
Dechlorane	-	-	-	56	51
Hexachloro 1, 3-Butadiene	-	-	-	-	20
Lithium Carbonate	2	-	-	-	-
Lithium Perchlorate	-	75	79	-	-
Magnesium	5	5	5	15	19
Potassium Perchlorate	65	-	-	-	-
Sodium Chloride	10	-	-	-	-
Hydrocarbon Binder	18	20	17	29	10

MEASURED AEROSOL ELEMENTAL COMPOSITION (CALSPAN)*

	CY85A	LiCl#1	LM9	LM11	LM12
Cl	48		82	45	58
Na	6		-	-	-
K	43		-	-	-
Mg	3		3	18	21
Li	< 1		14	-	-
C	-		-	≈36	≈20

* LiCl#1 not analyzed; believed similar to LM9.
Carbon data preliminary. Total insoluble content not available.

Pyrotechnics LM11 and LM12 generate smokes composed of $MgCl_2$ and carbon aerosol. The carbon component of these smokes results from the combustion of dechlorane which produces carbon aerosol and chlorine gas. The chlorine then combines with magnesium forming the hygroscopic $MgCl_2$ aerosol.

3.3 Extinction and Mass Yield Measurements

Figures 1 and 2 present the visible and IR wavelength nominal and payload mass extinction coefficient, the nominal and total pyrotechnic mass yield, and the aerosol mass growth factor for the LM9, LM11, LM12 and CY85A pyrotechnics at relative humidities of approximately 40 and 85 %. Definition of the extinction, yield and aerosol growth factors is provided in Appendix A.

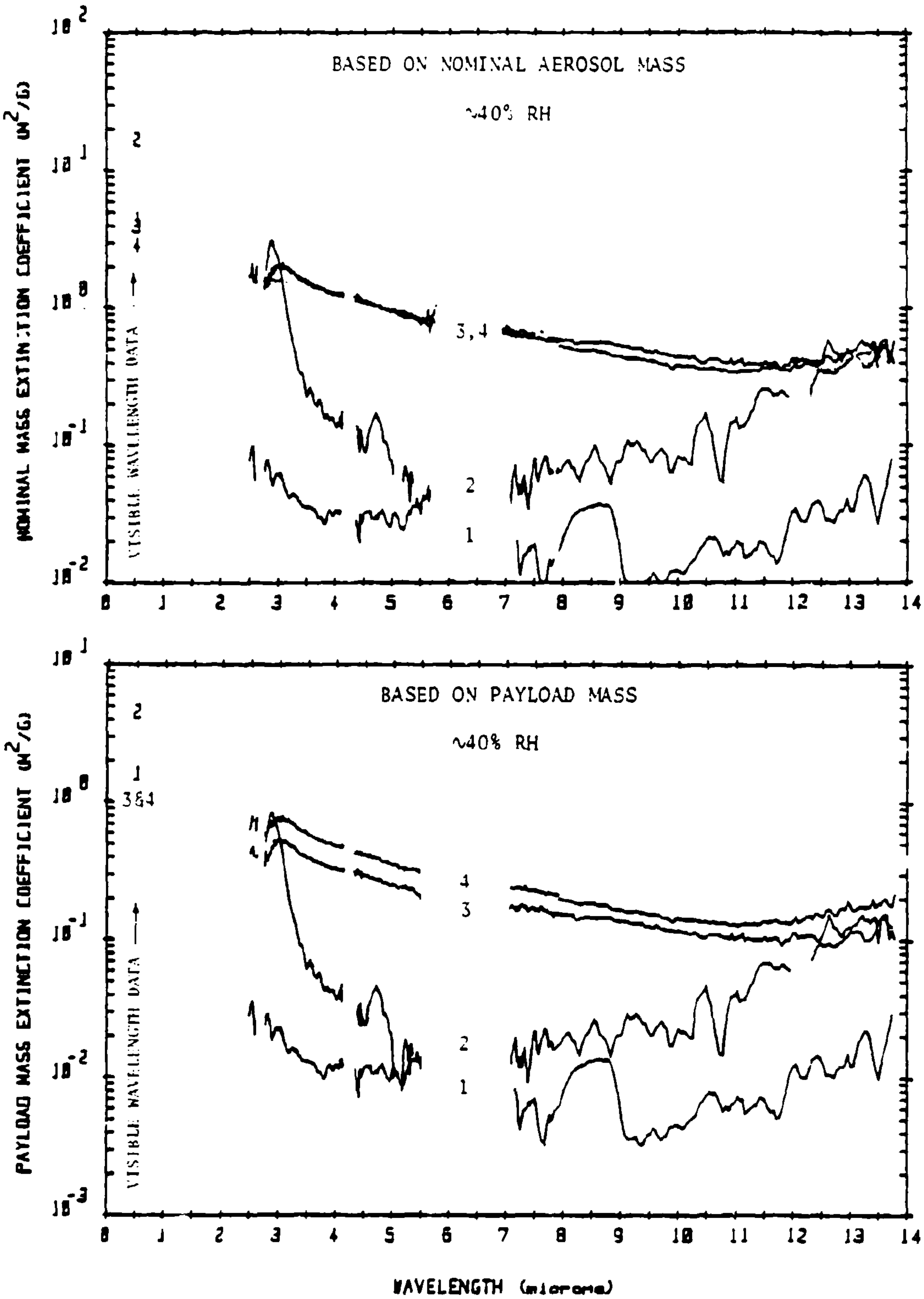
A limited comparison of the extinction characteristics of the NWC pyrotechnics to white phosphorus is provided in Appendix B.

As mentioned earlier, the LM9 pyrotechnic represents and improved version of LiCl#1. By reducing the binder content of the pyrotechnic, the pyrotechnic nominal mass yield was increased from 18% for LiCl#1 to 26% for LM9. Except for this difference in the pyrotechnic nominal mass yield, the two smokes are identical. Thus, of these two pyrotechnics, only the improved version, LM9, is discussed below.

From examination of Figures 1 and 2, two general conclusions may be immediately drawn:

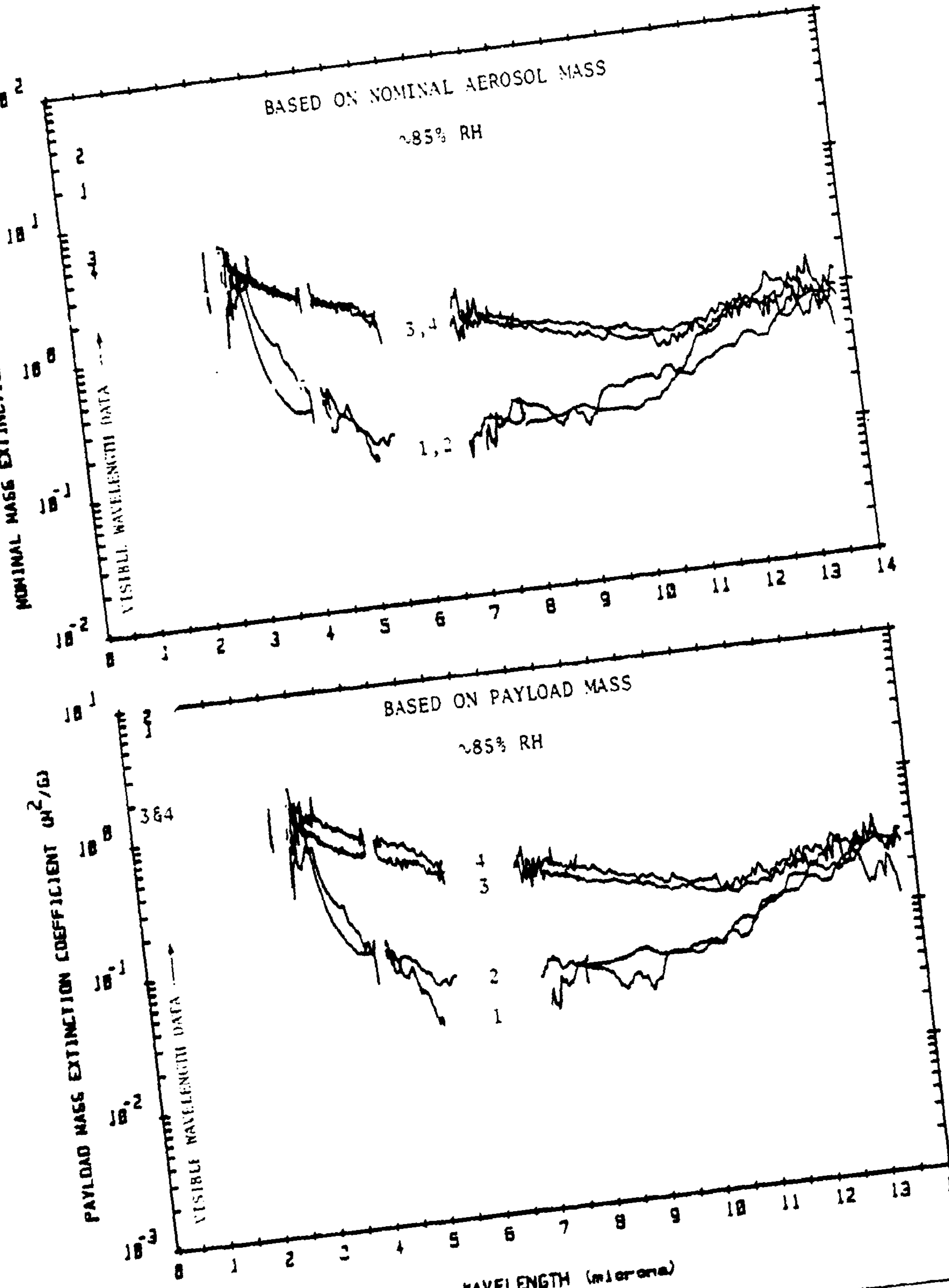
1. At low humidity, LM11 and LM12 provide up to 40 times greater IR wavelength extinction than CY85A and at high humidity, up to 10 times greater than CY85A.

2. At low humidity, LM9 provides approximately three times the extinction of CY85A over most of the 0.5-14 um wavelength region. At high humidity LM9 and CY85A are roughly equivalent.



Test No.	Payload	Label	Material	RH	Pyrotechnic Nominal Mass Yield	Pyrotechnic Total Mass Yield @ RH	Aerosol Mass Growth Factor
15	160 g	1	CY8SA	31%	37%	38%	1.05
16	80 g	2	LM 9	42%	27%	75%	2.77
17	80 g	3	LM 11	40%	26%	48%	1.85
18	80 g	4	LM 12	39%	38%	68%	1.80

Figure 1. Extinction Characteristics of the NWC Pyrotechnics at ~40% RH.



Test No.	Payload	Label	Material	RH	Pyrotechnic Nominal Mass Yield	Pyrotechnic Total Mass Yield @ RH	Aerosol Mass Growth Factor
19	80 g	1	CY85A	86%	35%	143%	4.04
20	80 g	2	LM 9	83%	25%	178%	7.24
23	80 g	3	LM 11	88%	27%	102%	3.81
22	80 g	4	LM 12	87%	36%	130%	3.62

Figure 2. Extinction Characteristics of the NWC Pyrotechnics at ~85% RH.

- LM11 and LM12

Two factors likely contribute to the superior IR wavelength extinction of LM11 and 12: absorption by carbon and relatively large particle size.

As discussed earlier, carbon is a major component of the LM11 and 12 smokes. Carbon is known to be an effective absorber of both visible and IR wavelength radiation (Pinto and Wiegand, 1979) and thus absorption is likely to be significant in these smokes.

Additional IR wavelength extinction may be due to scattering by relatively large particles in the smokes. While direct particle size measurements were not made, the average particle sizes of the LM11 and 12 smokes appear to be significantly greater than that of CY85A and LM9. The assumption of a larger particle size is based on the relatively rapid mass and extinction decay rates of the smokes relative to CY85A, and by simple observation of the smoke fall-out on the chamber floor.

While the extinction of LM11 and 12 exceeds that of CY85A in the IR, the reverse is true at visible wavelengths where LM11 and 12 provide only $\sim$25 and 60% of the extinction of CY85A at high and low humidity, respectively. The relatively lower effectiveness at visible wavelengths is attributed to the lower concentration of particles of visible wavelength size (i.e., effective scatterers) than in the CY85A smoke.

Though LM11 and 12 are quite similar, LM12 has a greater pyrotechnic nominal mass yield (37% vs 27%) making it the better of the two smokes.

- LM9

The LM9 pyrotechnic generates a LiCl aerosol and, thus, aerosol deliquescence is expected at approximately 13% RH, considerably lower than the $\sim$ 80% RH required for the complete deliquescence of the CY85A aerosol. The superior performance of LM9 relative to CY85A at low humidity ($\sim$40%) is attributed directly to the lower deliquescence humidity of the LM9 aerosol.

At 85% RH, LM9 again out performs CY85A. While both smokes have undergone complete deliquescence at this humidity, the larger aerosol mass growth factor for LM9 ($\sim$ 7.2) as compared to that for CY85A ($\sim$4.0) is apparently responsible for the superior performance of the LM9 smoke.

The relatively poor extinction performance of LM9 at IR wavelength relative to LM11 and 12, is attributed to small particle size and lack of absorption in the LM9 smoke, the same factors attributed to the poor IR extinction of CY85A.

SECTION 4

SIZE DISTRIBUTION MEASUREMENTS OF THE PYROTECHNIC SMOKES

During tests 1-14 measurements were made of the aerosol size distribution (0.01 - 10 um diameter) for pyrotechnics CY85A, LiCl#1, NWC 78, NWC 79 and NWC 164 (see Hanley, et.al., 1981 for composition data of pyrotechnics). In addition to determining the basic aerosol size distribution of the smokes, the effect of payload mass and pyrotechnic ventilation on the resultant aerosol size was investigated. The results of these measurements are presented in Table 3. Simultaneous measurement of aerosol size distribution was performed by NRL (Hoppel and Frick, 1982) and of the mass distribution by NWC (Dr. L. Mathews, unpublished).

NRL's participation in these tests was largely directed toward measurement of the aerosol size distribution and assessment of the related particle formation mechanisms. These topics are discussed in detail in the NRL report (Hoppel and Frick, 1982). Thus, Calspan's aerosol size measurements, obtained primarily for instrument comparison purposes, will be only briefly discussed.

To assess the dependence of aerosol size distribution on payload mass, tests 7-12 were performed. In each test, payloads of 0.5 and 5 g were ignited. As can be seen from Table 3, an increase in payload mass resulted in an increase in mean aerosol diameter (increasing from approximately 0.11 um for the 0.5 g payloads to 0.14 um for the 5 g payloads). Additional data obtained by NRL for a 160 g payload of CY85A during test 2 (for which Calspan instrumentation was overloaded) showed a further increase in the mean diameter to 0.25 um. The increase in aerosol size with increasing payload likely results from the combined effects of an increase in the concentration of condensable gases generated by the pyrotechnic and through aerosol coagulation within the chamber.

Tests 13 and 14 were performed to evaluate the influence of pyrotechnic ventilation upon the resultant aerosol size distribution. For test 13, the pyrotechnic was ventilated during combustion so as to rapidly dilute the condensable gases generated. As can be seen in Table 3, ventilation resulted in

CHAMBER TESTS
8-19 March 1982

TABLE 3: EAA AND ROYCO SIZE DISTRIBUTIONS; #/CC FOR INDICATED SIZE RANGE; DIAMETER (um)
@ APPROXIMATELY 10 MINUTES AFTER BURN; BACKGROUND AEROSOL FACTORED OUT

TEST NO.	PAYLOAD	RH	EAA .01-.0178	EAA .0178-.0316	EAA .0316-.0562	EAA .0562-.1	EAA .1-.178	EAA .178-.316	EAA .316-.562	EAA .562-1.0	ROYCO .316-.562	ROYCO .562-1.78	ROYCO 1.78-3.16	ROYCO 3.16-5.62	ROYCO 5.62-10.0	Mean Diam. (um)	Total #/cc
1	0.498 g CY85A	16%	1668	3173	1044	2042	3591	2460	754	207	126	9.7	0.093	0.027	0	0.107	14428
2	0.50 g CY85A	37%	1251	1503	783	2176	5085	2804	534	95	156	12.9	0.092	0.026	0.0053	0.125	13960
3	0.499 g LiCl	34%	2502	6346	3741	7726	9327	4231	1001	246	236	62.8	0.14	0.0052	0	0.101	34554
4[a]	0.508 g LiCl	73%	-	-	-	-	-	-	-	-	276	85.0	0.22	0	0	-	-
5[a]	0.3 g LiCl	84%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6[a]	80 g CY85A	89%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7[b]	0.517 g CY85A	38%	12093	19372	4524	4795	6459	3198	607	102	142	10.8	0.11	0.036	0.0026	0.058	50826
	+4.85 g CY85A	40%	7923	9686	5046	9635	28872	22128	5009	825	254	445.9	12.3	0.39	0.031	0.139	86399
8[b]	Torch Only	37%	44202	24382	1305	355	72	25	6.7	0	1.04	0.069	0	0.004	0		
	0.495 g LiCl	37%	15429	26553	6264	12121	13858	4440	727	119	219	57.0	0.14	0.013	0.001	0.065	79195
	+5.05 g LiCl	37%	21267	9686	10875	18071	48947	42201	16608	5739	105	307.0	210.0	1.0	0	0.145	159921
9	Torch Only	36%	0	0	0	0	0	0	0	0	0	0	0	0	0		
	0.488 g NWC 164	36%	1251	1670	696	1554	3567	2103	413	70	210	21.0	0.12	0.027	0.001	0.119	11173
	+5.0 g NWC 164	36%	5004	3173	2436	7104	23232	15203	2942	488	234	443.0	38.0	0.50	0.0075	0.149	58221
10	Torch Only	35%	0	0	0	0	0	0	0	0	0	0	0	0	0		
	0.506 g LiCl	35%	2985	4342	2436	7104	9278	3924	867	172	241	60.6	0.088	0.0012	0	0.108	29783
	+5.0 g LiCl	35%	16680	12525	8352	26152	69553	44870	11599	2576	145	382.0	130.0	0.089	0	0.140	184516
11	Torch Only	30%	0	0	0	0	0	0	0	0	0	0	0	0	0		
	0.492 g NWC 79	30%	1668	668	435	932	2603	1599	314	46	163	14.0	0.12	0.029	0.0013	0.118	8157
	+5.0 g NWC 79	30%	7089	5511	1653	5950	19497	12718	2448	391	287	447.0	33.0	0.92	0.071	0.137	54266
12	Torch Only	37%	0	0	0	0	0	0	0	0	0	0	0	0	0		
	0.508 g NWC 78	37%	3336	5845	1479	1376	1952	1119	227	42	116	9.9	0.117	0.029	0.0025	0.062	15288
	+5.05 g NWC 78	41%	3336	7682	2958	6305	13472	8130	1581	274	338	407.0	16.1	0.688	0.0306	0.125	43265
13 Ventilated Burn	Torch Only	39%	417	334	0	0	0	0	0	0	0	0	0	0	0		
	0.501 g CY85A	39%	11259	22378	13050	38495	32680	6359	707	116	237	0.672	0.090	0.023	0	0.0816	124693
	+5.0 g CY85A	40%	2502	37575	15399	75214	173495	56211	7170	1021	435	21.1	0.943	0.192	.015	0.124	364220
14 Chimney Burn	Torch Only	40%	0	0	0	0	0	0	0	0	0	0	0	0	0		
	0.49 g CY85A	40%	2502	3340	1305	2797	3760	1734	334	63	119	15.3	0.083	0.015	.0013	0.0892	15679
	+5.1 g CY85A	40%	6255	7515	2958	6127	13424	8389	1701	316	323	361.0	43.1	0.802	.023	0.120	46084

[a] EAA Failure

[b] Smoke contaminated by aerosol generated from salted torch tip; beginning with Test 9 tip was cleaned prior to each test.

a decrease in the mean diameter with an increase in the total number of particles produced.

In contrast to the ventilated tests, test 14 was conducted with a chimney, 6 inches in diameter and 4 feet long, placed over the pyrotechnic during combustion so as to increase the concentration of condensable gases. It was expected that the increased gas concentration would lead to larger particles upon condensation. Unfortunately, a significant fraction of the smoke aerosol deposited upon the walls of the chimney preventing a meaningful interpretation of the resultant size distribution data.

Section 5

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Results from this year's tests show that the new NWC smokes significantly outperform all previous NWC smokes tested by Calspan on this program. At IR wavelengths the newly developed LM12 pyrotechnic provides up to 40 times the extinction of CY85A. Its superior IR performance is attributed to the combined effects of absorption by the ~25% (by weight) carbon content of the LM12 smoke and scattering by relatively large smoke aerosol.

Improvements were also measured for visible wavelength extinction. The LM9 pyrotechnic, generating a very hygroscopic LiCl aerosol, provided from 2 to 4 times the extinction of CY85A, chiefly through scattering effects.

Specifically, the major conclusions drawn from this year's effort are:

1. Low humidity IR wavelength (3-12 um) obscuration provided by the LM11 and LM12 pyrotechnics is up to 40 times the obscuration provided by CY85A and, at high humidity, up to 10 times greater than CY85A.

2. Visible wavelength (0.5 um) obscuration of LM11 and LM12 at low humidity approaches that of CY85A but at high humidity LM11 and LM12 provide only ~25% of the visible wavelength obscuration of CY85A.

3. LM9 provided the greatest visible wavelength obscuration of all the NWC smokes evaluated.

4. Based on payload mass, LM9 provides approximately three times the obscuration of CY85A at low hum dity over nearly all wavelengths measured (0.5-14 um). At high humidity, the obscuration provided by LM9 and CY85A is nearly equivalent.

Recommendations

- The LM11 and 12 pyrotechnics represent a major advancement in the development of an effective IR obscurant derived from an alkali-halide pyrotechnic. The tests conducted on this year's program were limited to the basic measurement of the pyrotechnics' mass extinction coefficient. To gain a sound understanding of the extinction mechanisms responsible for the smokes' obscuration effectiveness and potential means of increasing their obscuration, measurements of the smokes' aerosol size distribution, particle morphology and fallout rate must be made.

- An important component of a pyrotechnics performance is the fraction of the total pyrotechnic which actually becomes the smoke aerosol (i.e., the pyrotechnic nominal mass yield). As observed in last year's study (Hanley, et.al., 1981) and recently in a demonstration conducted at NWC for which a thirty pound payload of CY85A was combusted, the yield of the pyrotechnic increases with payload mass. Thus, yields obtained from the relatively small payloads used in the chamber tests may underestimate the yield of a field-sized (presently ∿80 pounds) payload. Therefore, an evaluation should be made to determine the pyrotechnic yield for field-size payloads. Preferably, this evaluation would consist of both a theoretical calculation of the maximum potential yield based on pyrotechnic composition, and large scale chamber tests in which progressively larger payloads could be ignited to define the payload to yield relationship.

- A major factor affecting the ultimate utilization of the recently developed NWC smokes is their performance relative to the Navy smokes presently deployed. Thus, a comprehensive evaluation of the obscuration potential, handling safety, smoke toxicity and smoke persistance should be performed for both the presently deployed and newly developed smokes.

Based on the conclusions and above discussion, it is recommended that future study include the following:

1. Continued evaluation of the LM11 and LM12 pyrotechnics to obtain data on particle size distribution, particle morphology (particularly of the carbon aerosol), particle fallout rate, and carbon content of the smokes for development of optimum pyrotechnic formulation.

2. Evaluation of the pyrotechnic nominal mass yield for field-sized payloads of the NWC smokes.

3. A comprehensive evaluation of the performance of the NWC pyrotechnics to presently deployed Navy smokes.

4. Evaluation of possible health hazards associated with the inhalation of the LM11 and LM12 smokes.

REFERENCES

1. Mack, E.J., R.J. Anderson and J.T. Hanley, 1978: "A Preliminary Investigation of the Production of Stable Fogs under Subsaturated Conditions," Calspan Report No. 6287-M-1, 103 pp Calspan Corp., Buffalo, NY, 14225.

2. Mack, E.J. and J.T. Hanley, 1980: "A Laboratory Study of Artificial Fogs Produced under Subsaturated Conditions," Calspan Report No. 6510-M-1, 37 pp Calspan Corp., Buffalo, NY 14225.

3. Hanley, J.T. and E.J. Mack, 1980: "A Laboratory Investigation of Aerosol and Extinction Characteristics for Salty Dog, NWC 29 and NWC 78 Pyrotechnics," Calspan Report No. 6665-M-1, 40 pp, Calspan Corp., Buffalo, NY 14225.

4. Hanley, J.T., B.J. Wattle and E.J. Mack, 1981: "Extinction Characteristics of Pyrotechnically-Generated Alkali-Halide Smokes," Calspan Report No. 6855-M-1, 39 pp, Calspan Corp., Buffalo, NY 14225.

5. Tarnove, T.L., 1980: "Studies of the Chemistry of the Formation of Phosphorus-Derived Smokes and Their Implications for Phosphorus Smoke Munitions," ARCSL-TR-80049.

6. Pinto, J. and D. Wiegand: "Experimental Studies of the Optical Extinction of Various Forms of Carbon," Proceedings of the 1979 Chemical Systems Laboratory Scientific Conference on Obscuration and Aerosol Research, December 1980.

7. Hoppel, W.A. and G.M. Frick, 1982: "Size Distributions of Pyrotechnically Generated Hygroscopic Aerosols," NRL Memorandum Report 4946.

APPENDIX A

EXTINCTION AND MASS YIELD PARAMETERS

There are numerous parameters which may be used to characterize the extinction effectiveness of an obscurant. Which parameter, or combination of parameters, is chosen will depend upon the specific applications involved. In the development of an obscurant, it is often desirable to separate the effects of dissemination efficiency and aerosol extinction. By doing so, each phase may be evaluated, studied and improved separately. Additionally, this allows for comparison to other obscurants which may differ fundamentally in the means of dissemination and/or aerosol properties.

When discussing hygroscopic aerosols, confusion sometimes occurs with reference to "aerosol mass" as to whether this is to include mass resulting from processes such as oxidation, hydration and condensation or, is solely the mass of the aerosol which originated from the pyrotechnic. To avoid this confusion in this report, the term "total aerosol mass" will refer to the entire aerosol mass. The term "nominal aerosol mass" will refer only to the aerosol mass which originated directly from the pyrotechnic and will not include, therefore, any additional mass as may be supplied by the environment. Thus, for the alkali-halide aerosols, the nominal mass is the total aerosol mass minus the mass of condensed water; for a phosphorus smoke aerosol, the nominal mass would be the total aerosol mass minus the mass due to oxidation, hydration and condensation.

In light of the above, extinction measurements are reported in terms of both a dissemination efficiency and an aerosol extinction parameter. Dissemination efficiency is presented in terms of the pyrotechnic nominal mass yield computed from

NOMINAL MASS YIELD = (NOMINAL AEROSOL MASS)/(PAYLOAD MASS).

Extinction measurements are presented in terms of the nominal mass extinction coefficient computed from

$$\text{NOMINAL MASS EXTINCTION COEFFICIENT} = \frac{\text{(EXTINCTION COEFFICIENT)}}{\text{(NOMINAL AEROSOL MASS PER UNIT CLOUD VOLUME)}}$$

(where the extinction coefficient is obtained from Beer's Law, $I=I_o e^{-\beta x}$).

Thus, the extinction coefficient is normalized by the mass concentration of only the aerosol material which originates from the pyrotechnic. This parameter provides a means of ranking the extinction effectiveness of different aerosols.

Additionally, extinction measurements are presented normalized directly to the payload mass computed from

$$\text{PAYLOAD MASS EXTINCTION COEFFICIENT} = \frac{\text{(EXTINCTION COEFFICIENT)}}{\text{(PAYLOAD MASS PER UNIT CLOUD VOLUME)}}$$

Clearly, the payload mass extinction coefficient is mathematically equal to the product of the nominal mass yield and nominal mass extinction coefficient.

When dealing with a deliquescent aerosol, where particle size and, hence, extinction, is a function of humidity, a measure of the aerosol growth is useful in interpreting the extinction data. Aerosol growth will be represented by the aerosol mass growth factor computed from

AEROSOL MASS GROWTH FACTOR = (TOTAL AEROSOL MASS)/(NOMINAL AEROSOL MASS).

Also, the added mass due to condensation will increase the total mass yield of the pyrotechnic. This is reported as the pyrotechnic total mass yield computed from

TOTAL MASS YIELD (@ RH) = (TOTAL AEROSOL MASS (@ RH))/(PAYLOAD MASS).

APPENDIX B

A LIMITED COMPARISON OF THE NWC PYROTECHNICS TO PURE WHITE PHOSPHORUS

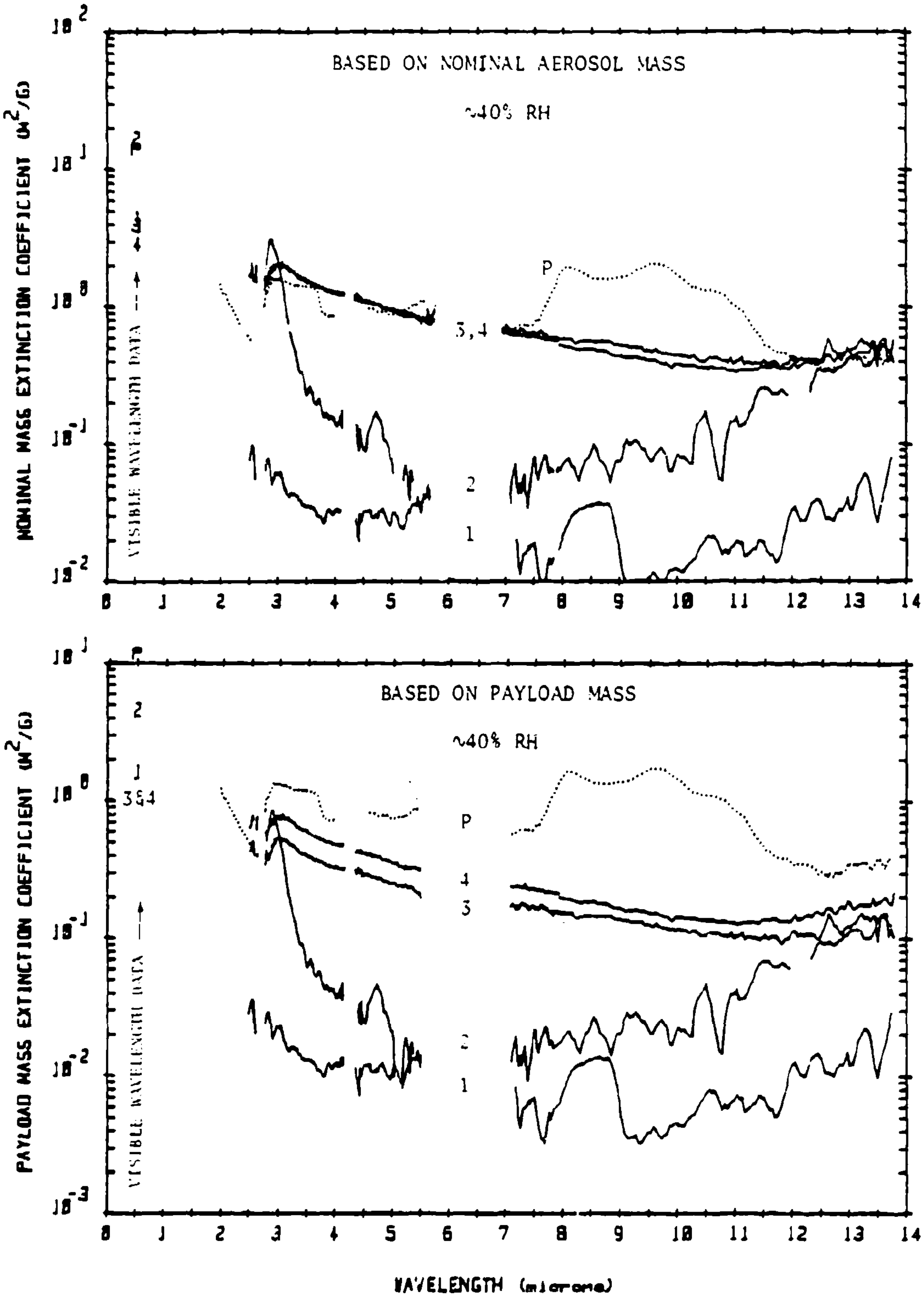
Figures B-1 and B-2 present a comparison of the extinction effectiveness of the alkali-halide smokes to a phosphorus smoke at 40 and 90% RH. The payload used in the phosphorus tests were purified laboratory grade white phosphorus.

Unlike the alkali-halide smokes for which the mass loading samples were baked and reweighed to measure the nominal aerosol mass, the nominal aerosol mass of the phosphorus smokes was computed by dividing the total aerosol mass (as measured by mass loading filter samples) by the assumed phosphorus aerosol mass growth factor as given by Tarnove (1979).

As can be seen in the figures, the IR wavelength nominal mass extinction coefficient for the LM11 and 12 smokes is equal to that of the phosphorus except in the 8-11 um regime where phosphorus has P=0 absorption bands.

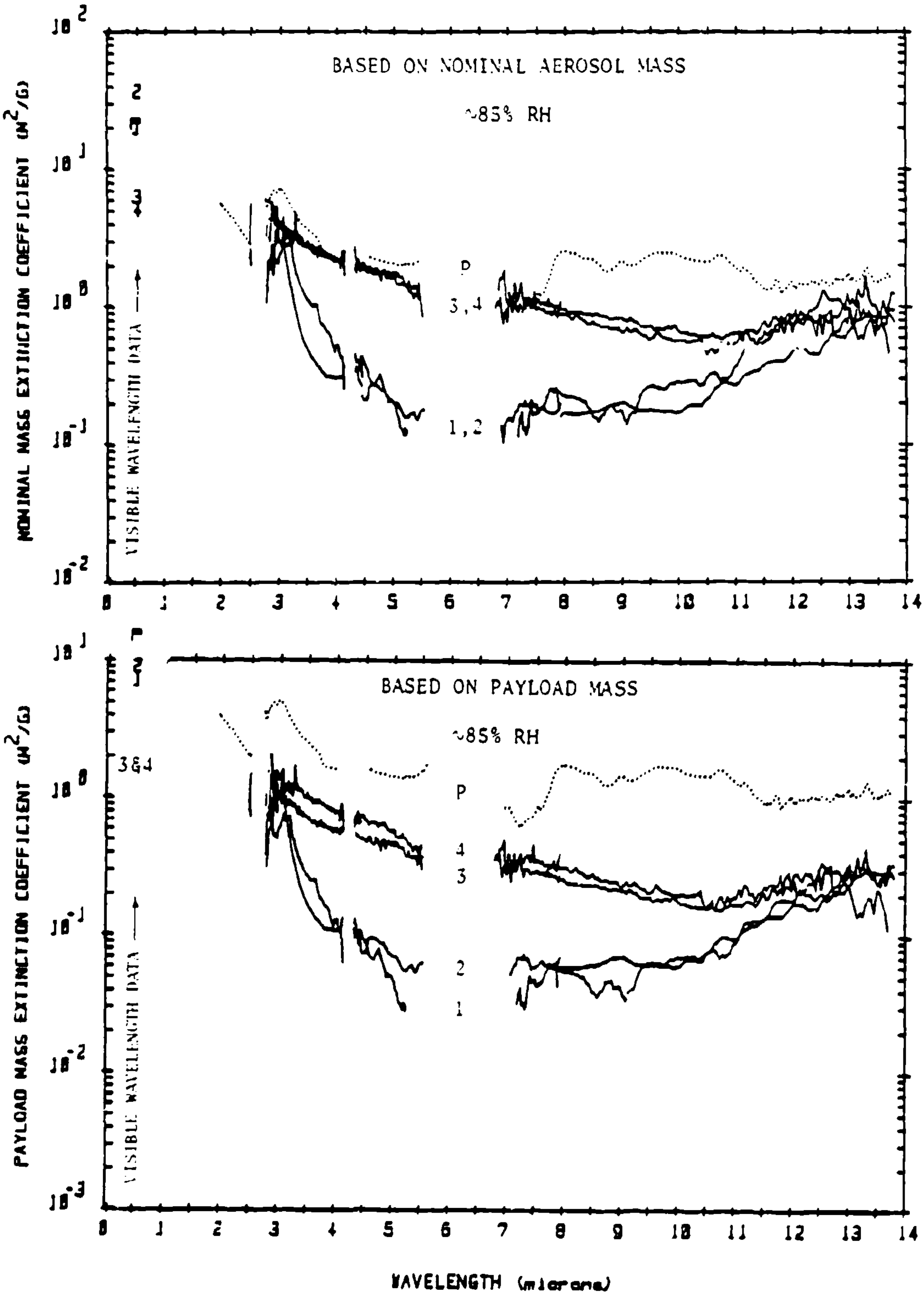
Additionally, the visible wavelength nominal extinction coefficient for the LM9 smoke equals that of phosphorus at low humidity and exceeds phosphorus by approximately 50% at high humidity.

Relative to payload mass, the white phosphorus outperformed the NWC smokes, though the new smokes have significantly narrowed the gap. It must be emphasized that the phosphorus used was purified, laboratory grade white phosphorus which likely has a higher yield than actual munition phosphorus. Thus, the obscuration potential of the NWC smokes may be closer to that of actual phosphorus munitions than is indicated in the figures.



Test No.	Payload	Label	Material	RH	Pyrotechnic Nominal Mass Yield	Pyrotechnic Total Mass Yield @ RH	Aerosol Mass Growth Factor
15	160 g	1	CY85A	31%	37%	38%	1.05
16	80 g	2	LM 9	42%	27%	75%	2.77
17	80 g	3	LM 11	40%	26%	48%	1.85
18	80 g	4	LM 12	39%	38%	68%	1.80
-	22.5 g	P	WHITE PHOSPHORUS	40%	84%	329%	3.9

Figure B-1. Comparison of the Extinction Characteristics of the NWC Pyrotechnics to White Phosphorus at ~40% RH.



Test No.	Payload	Label	Material	RH	Pyrotechnic Nominal Mass Yield	Pyrotechnic Total Mass Yield @ RH	Aerosol Mass Growth Factor
19	80 g	1	CY85A	86%	35%	143%	4.04
20	80 g	2	LM 9	83%	25%	178%	7.24
23	80 g	3	LM 11	88%	27%	102%	3.81
22	80 g	4	LM 12	87%	36%	130%	3.62
-	11.25 g	P	WHITE PHOSPHORUS	91%	70%	360%	8.0

Figure B-2. Comparison of the Extinction Characteristics of the NWC Pyrotechnics to White Phosphorus at ~85% RH.